Electromagnetic emission from axionic cloud

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1.Introduction

Based on arXiv:1811.04950 and PRD.99.035006

◉ Axions are key particles beyond SM.

- QCD axion
  - Strong CP problem

$$\mathscr{L}_{\mathrm{QCD}} = \mathscr{L}_{\mathrm{quark}} + \mathscr{L}_{\mathrm{SU(3)}} + \underline{\tilde{\Theta}\frac{g^2}{32\pi^2}G^{a\mu\nu}\tilde{G}_{a\mu\nu}}$$

$|\tilde{\Theta}| < 10^{-9}$: Why this value is small ?

phase of quark mass matrix

$$\tilde{\Theta} = \Theta + \mathrm{Arg\ Det}M$$

parameter of correct vacuum

  - Peccei Quinn Mechanism is one of the plausible solution.
    - Light scalar field "axion" was predicted

Φ : Axion field $\qquad$ μ : mass of axion

- String axion
  - String theory also predict the scalar field with very light mass.
- Axion is dark matter candidates.

◉ Properties of axions around BHs

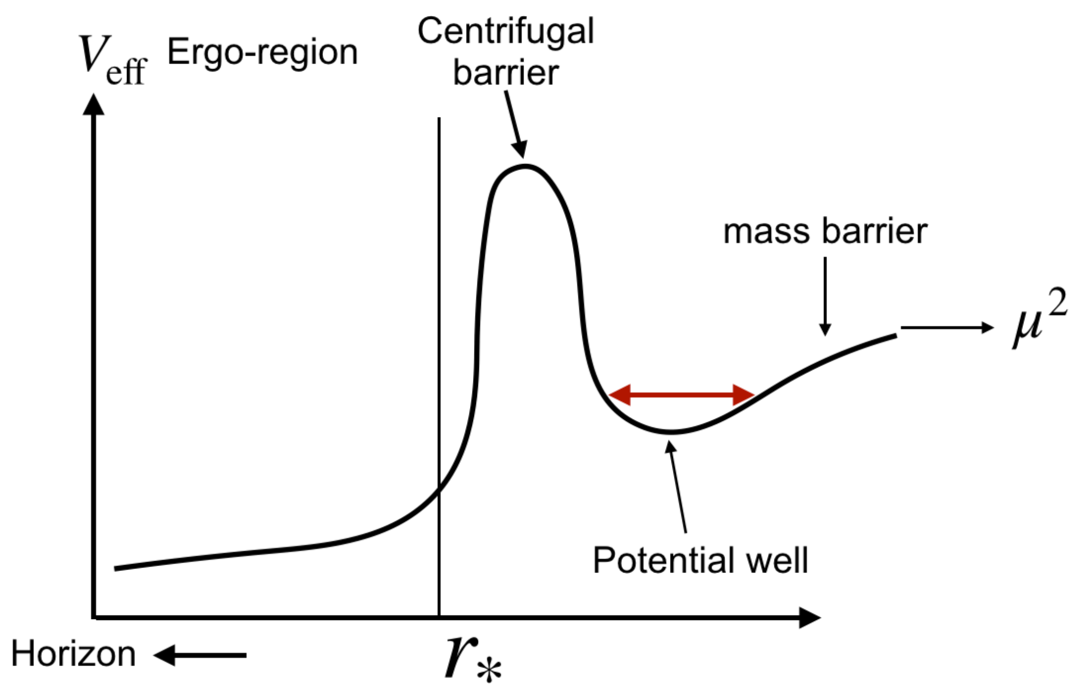
- Super-radiance
  - Relevant mass range : $10^{-22}\mathrm{eV} < \mu < 10^{-10}\mathrm{eV}$
  - condition : $\omega < m\Omega_{\mathrm{H}}$

Ω_{H} : angular velocity

$\Phi(x) = e^{-i\omega t}e^{im\phi}S_{lm}(\theta)R_{lm}(r)$

- Axion can localize as cloud around BH. (axionic cloud)

$$r_{\mathrm{cloud}} \sim \frac{(l+n+1)^2}{(M\mu)^2}M$$



◉ Interaction with photon

$\frac{k_a}{2}\Phi {}^{*}F^{\mu\nu}F_{\mu\nu}$: axionic coupling

$\frac{(k_s\Phi)^p}{4}F^{\mu\nu}F_{\mu\nu}$: scalar type coupling

- We consider the effect of the coupling in the could.
- Can the cloud emit photons ?

2.Simple toy model

◉ EM field grows exponentially under spatially uniform coherent oscillating axion field. (Sen(2018))

- Maxwell equation with uniform coherent oscillating axion field

$$\nabla_\mu F^{\mu\nu} = 2k_a \tilde{F}_{\nu\mu} \nabla^\mu \underline{\Phi} \qquad \Phi = \Phi_0 e^{-i\mu t} + \Phi_0^* e^{i\mu t}$$

μ : axion's mass

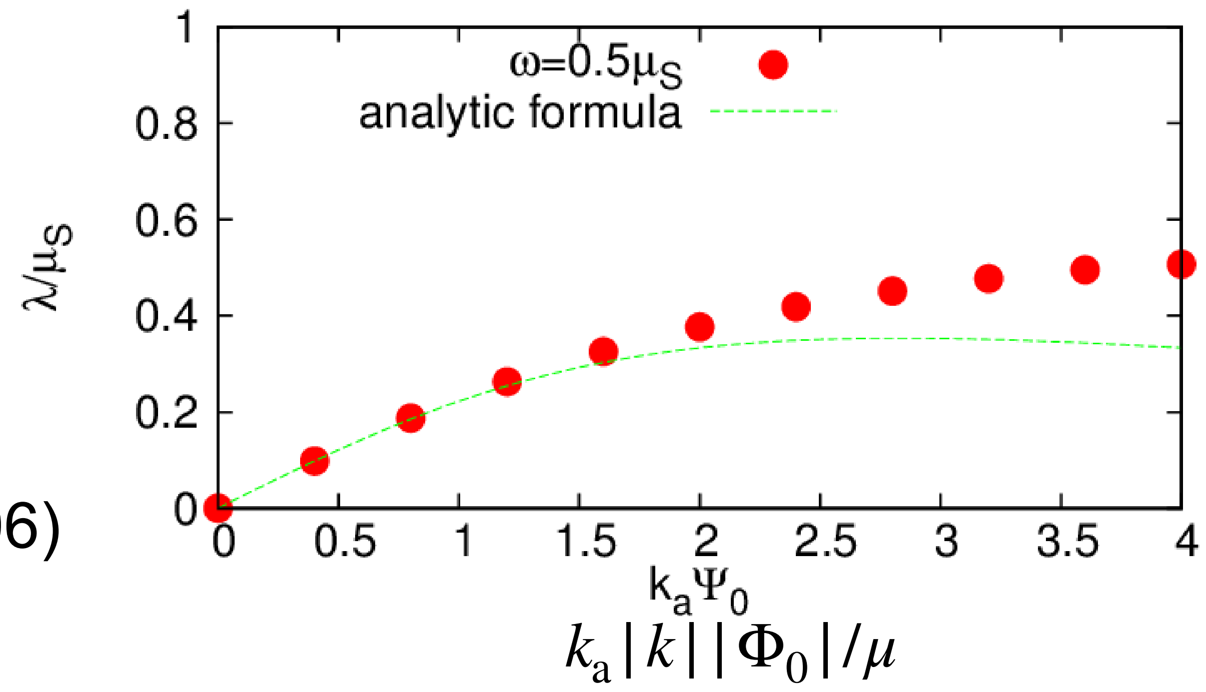
- We use following ansatz

$$A_\mu(\vec{x}, t) = \frac{1}{2\sqrt{V}} \sum_{\vec{k}} \left(\underline{\alpha_\mu(\vec{k}, t)} e^{i(\vec{k}\cdot\vec{x} - \omega_{\vec{k}} t)} + \underline{\alpha_\mu^*(\vec{k}, t)} e^{-i(\vec{k}\cdot\vec{x} - \omega_{\vec{k}} t)} \right)$$

- Coupled ordinary differential eqs. for transverse modes : $\tilde{\alpha}_{(I)}(t, \omega)$
- We can show that
  - the fastest growing mode : $\omega = 0.5\mu$
  - $\tilde{\alpha}_{(I)}(t, \omega = 0.5\mu) \sim e^{\lambda_a t}$

$$\lambda_a = \frac{\mu\epsilon}{1 + \frac{1}{2}\epsilon^2} \qquad \epsilon = k_a |k| |\Phi_0|$$

(PRD.99.035006)



◉ BLAST(**B**lack hole **L**asers powered by **A**xion **S**uper-radian**T** instabilities) (J.G.Rosa et al(2018))

- From Boltzmann equation (for 2p state)

N_ϕ : number of axions

N_γ : number of photons

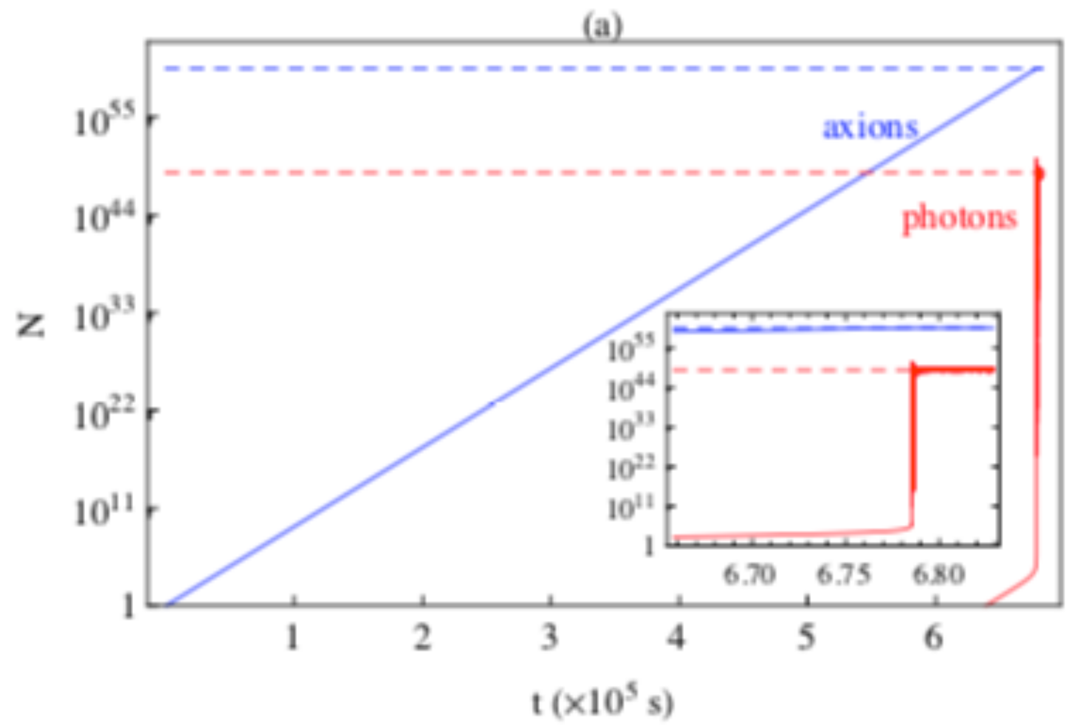
$$\frac{dN_\phi}{dt} = \Gamma_s N_\phi - \Gamma_\phi \left(N_\phi (1 + AN_\gamma) - B_1 N_\gamma^2 \right)$$

super-radiance effect

from interaction

$$\frac{dN_\gamma}{dt} = -\Gamma_e N_\gamma + 2\Gamma_\phi \left(N_\phi (1 + AN_\gamma) - BN_\gamma^2 \right)$$

escape from cloud



From PRL120.231102

- They predicted bright laser from axionic cloud around Kerr BHs.

3.What we want to do

◉ We solve Klein-Gordon equation and Maxwell equation with interaction around Kerr background.

$$\begin{cases} (\nabla^2 - \mu^2)\Phi = \dfrac{k_{\rm a}}{2}\tilde{F}_{\mu\nu}F^{\mu\nu} \\ \nabla_\mu F^{\mu\nu} = 2k_{\rm a}\tilde{F}_{\nu\mu}\nabla^\mu\Phi \end{cases}$$

4.Formulation & Initial data

◉ Back ground metric : Kerr BHs (Kerr Schild coordinate)

$$ds^2 = (\eta_{\mu\nu} + 2Hl_\mu l_\nu)dx^\mu dx^\nu \qquad H = \frac{r^3 M}{r^4 + a^2 z^2} \qquad l_\mu = \left(1, \frac{rx + ay}{r^2 + a^2}, \frac{-ax + ry}{r^2 + a^2}, \frac{z}{r}\right)$$

◉ 3+1 decomposition

- Evolution equation for scalar field.
- Evolution equation for EM field.
- Constraint equation (Gauss's law).
- Constraint damping sheceme.

Variables
$(\Phi, \Pi, \mathscr{A}_i, A_\phi, E^i, Z)$

◉ Initial data

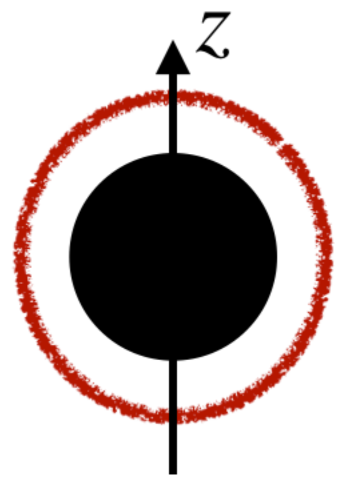
- Scalar field : axion cloud $\Phi = A_0 g(\tilde{r})\cos(\varphi - \mu t)\sin\theta$

$g(\tilde{r}) = \tilde{r}e^{-\tilde{r}/2}$
$\tilde{r} = rM\mu^2$

$k_{\rm a}A_0$: effective coupling for EM field

- EM field
  - 1. extended profile

$$E^\varphi = E_0 e^{-(\frac{r-r_0}{w})^2} \qquad E^r = E^\theta = B^i = 0$$



  - 2. localized profile

$$E^\varphi = E_0 e^{-(\frac{r-r_0}{w})^2}\Theta(\theta) \quad E^r = E^\theta = B^i = 0$$

$$\Theta(\theta) = \begin{cases} \sin^4(4\theta) & (0 \le \theta < \frac{\pi}{4}) \\ 0 & (\frac{\pi}{4} \le \theta < \pi) \end{cases}$$

initial parameter : E_0, r_0, w

(These profile satisfy Gauss's law.)

◉ Our numerical code

- Our numerical code is written in C++
- Fixed mesh refinement
- BH excision

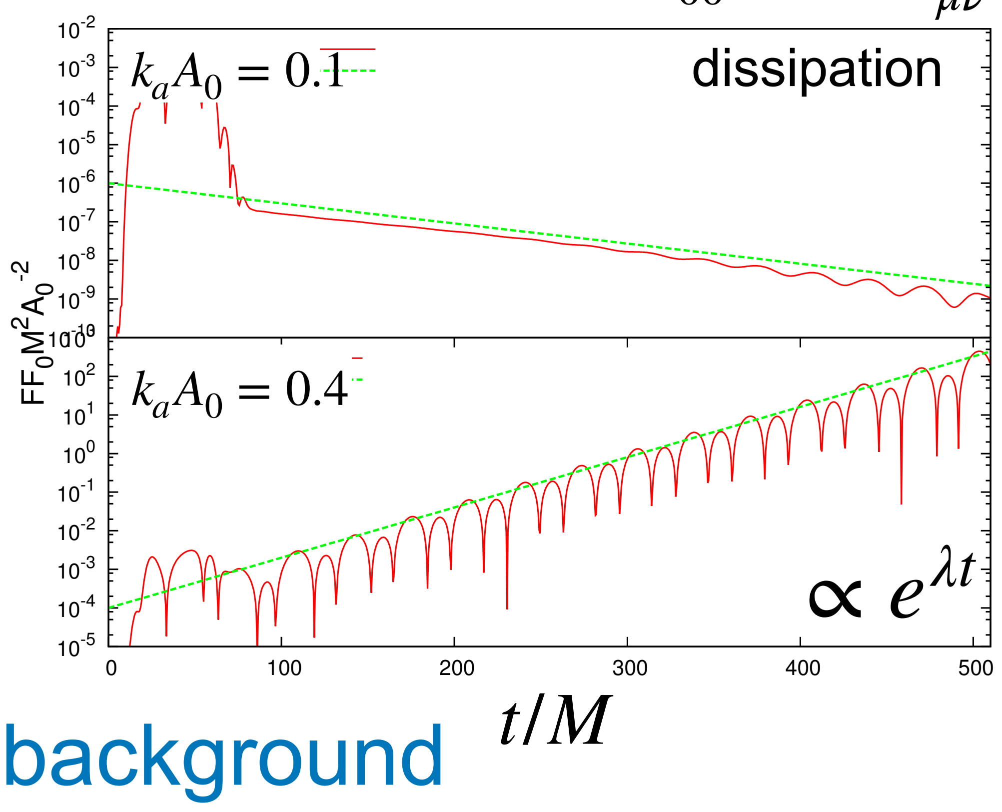
5.Result

1 . EM field under the fixed axion cloud in flat space.

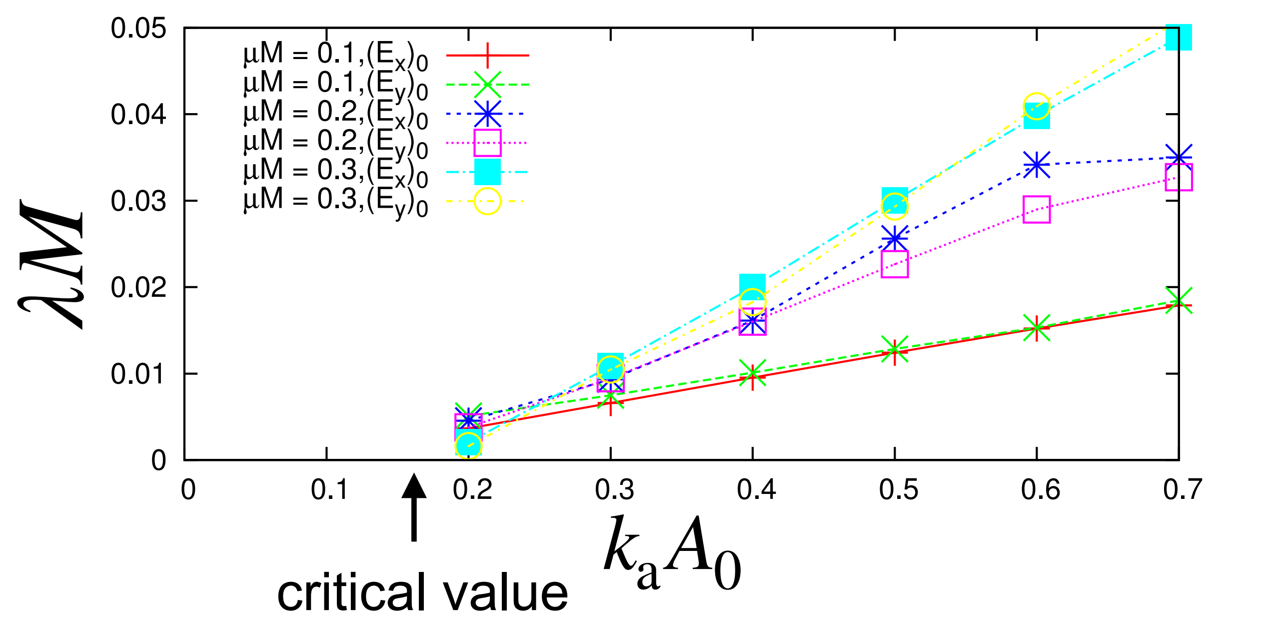
cf: $(FF)_{00} = \int d\Omega F^{\mu\nu} F_{\nu\nu} Y_{00}$

$$\nabla_\mu F^{\mu\nu} = 2k_a \tilde{F}_{\nu\mu} \nabla^\mu \Phi \longleftarrow \text{axion cloud : } \Phi = A_0 g(\tilde{r}) \cos(\varphi - \mu t) \sin\theta$$

Time evolution of Y_{00} of $F^{\mu\nu}F_{\mu\nu}$



Relation between λM and $k_a A_0$ for each mass μM



2 . Kerr background

- Scenario ($k_a A_0 >$ threshold)
  - 1.Initial EM pulse dissipates.
  - 2.EM field grows exponentially.
  - 3.Energy of EM field propagates as radiations.($\omega = 0.5\mu$)
  - 4.Energy of scalar field decrease, and new coupling is below the threshold.

- We get
  - luminosity formula:

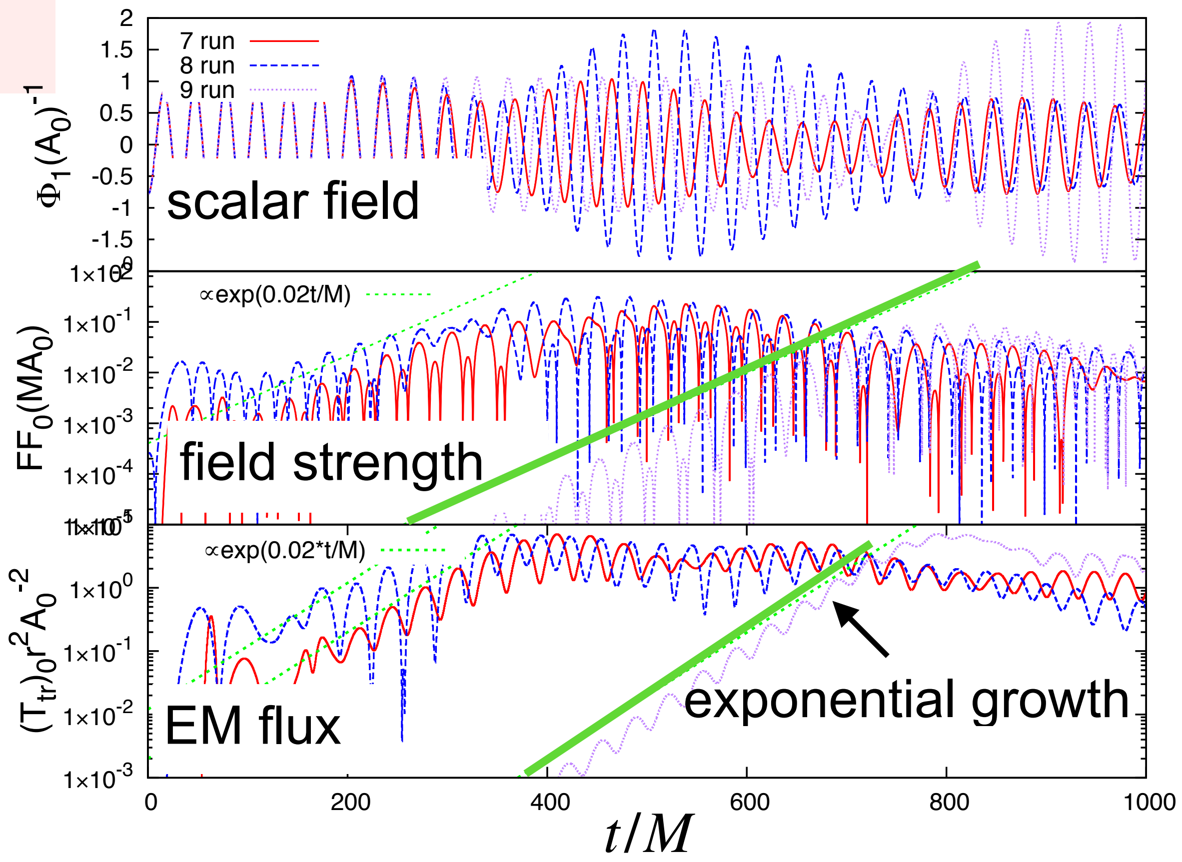
M : BH mass
M_S : total mass of axion cloud

$$\frac{dE}{dt} = 5.0 \times 10^{-6} \left(\frac{M_S}{M}\right) \frac{c^5}{G}$$

for $k_a A_0 = 0.3 - 0.4$

  - threshold for the burst :

$$\frac{\sqrt{\hbar}}{k_a} < 6 \times 10^{18} \left(\frac{M_S}{M}\right)^{1/2} (\mu M)^2 \text{ GeV}$$



3 . Super-radiance effect.

- We add term to scalar field eq. which induces “super-radiant” like effect.

$$g^{\mu\nu} \nabla_\mu \nabla_\nu \Phi + C\frac{\partial \Phi}{\partial t} = \mu^2 \Phi + \frac{k_a}{2} \tilde{F}_{\mu\nu} F^{\mu\nu}$$

“super-radiance” time scale $\sim 1/C$

- The burst is induced by the “super-radiance” like effect.

6.Summary

- We showed that if the effective coupling is larger than thermos hold, axionic cloud emits photons.
- We get similar result for scalar type coupling.